NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

The Promises and Challenges of Algal-Derived Biofuels

Clean Cities Webinar

October 15, 2009

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National Bioenergy Center
&
NREL C2B2 Site Director

Outline

Biofuels challenges: 2007 Renewable Fuels Standard Mandates

Why produce biofuels from microalgae?

DOE's Aquatic Species Program (what's different today?)

Technology challenges: Myth vs Reality

Recent Algal Biofuels Reports, Workshops and Roadmapping Efforts

New DOE funding opportunity: Algal Biofuels Consortium

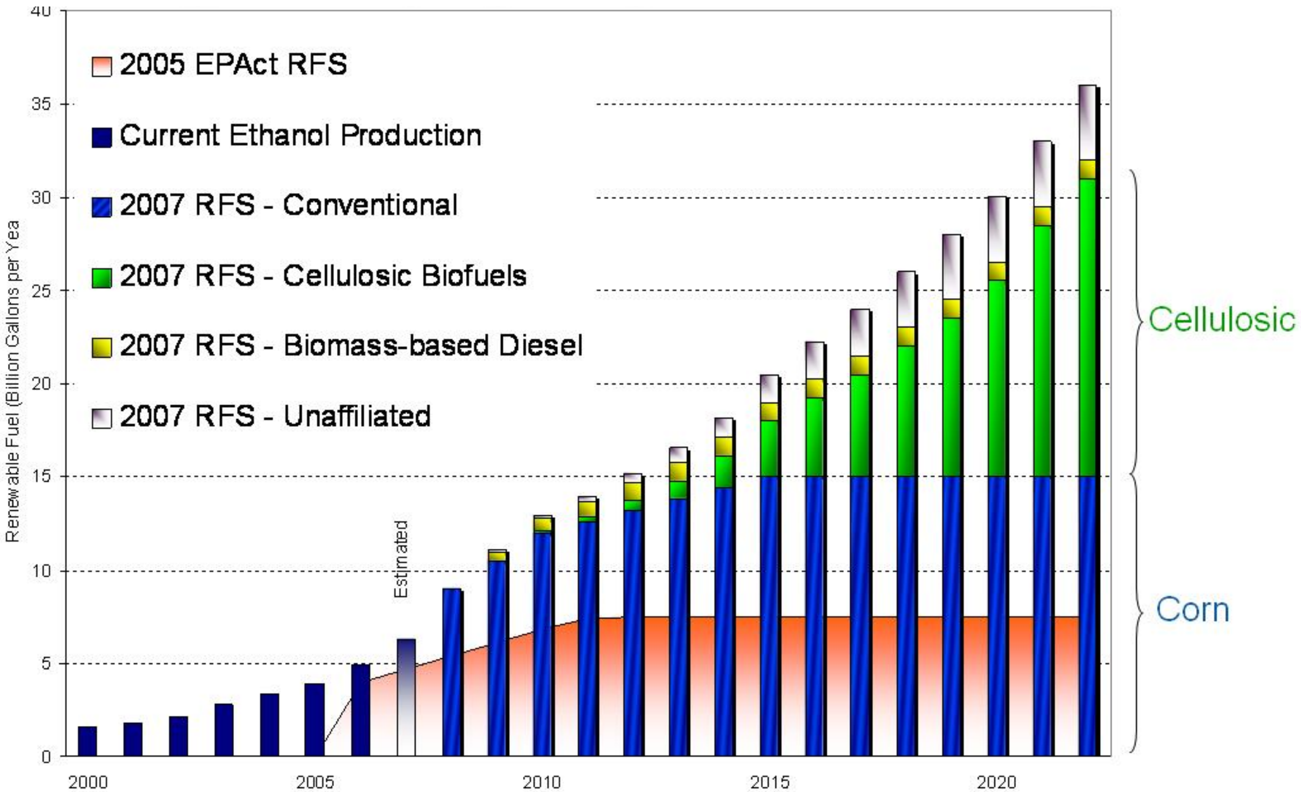
NREL's re-established algal biofuels research program

Advanced Biofuels in 2007 EISA

2007 RFS Does Not Mention Algae

EISA Renewable Fuel Standard

36 billion gallons of renewable fuels by 2022



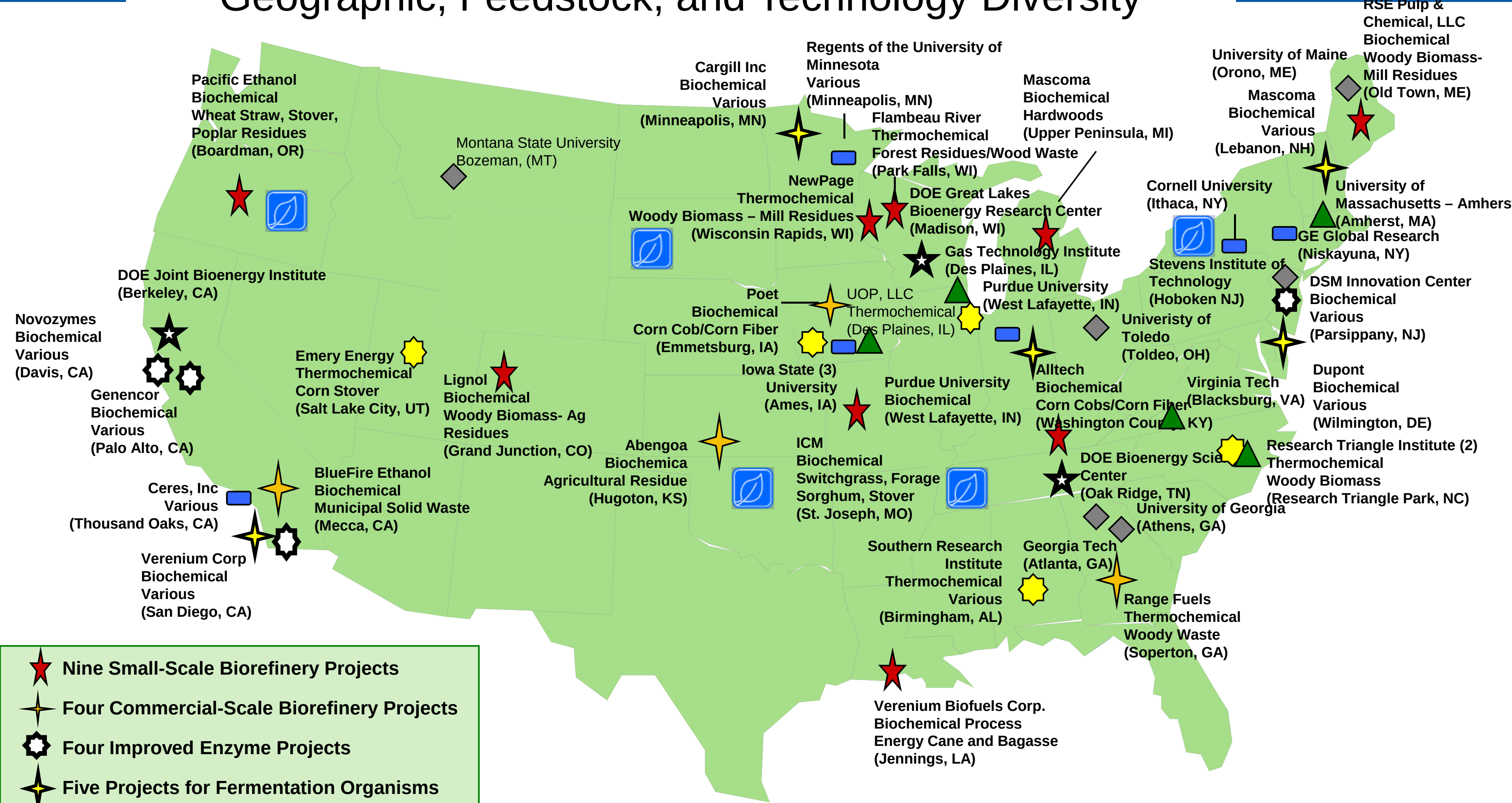
Source: EISA 2007, Sec. 202, p. 121 Stat 1522-1523

National Renewable Energy Laboratory

Innovation for Our Energy Futu

Major DOE Biofuels Project Locations

Geographic, Feedstock, and Technology Diversity



- Nine Small-Scale Biorefinery Projects
- Four Commercial-Scale Biorefinery Projects
- Four Improved Enzyme Projects
- Five Projects for Fermentation Organisms
- Five Thermochemical Syngas Projects
- Three Office of Science Bioenergy Centers
- DOE Joint Solicitation Biomass Projects
- Five Thermochemical Bio-Oil Projects
- Six University Projects

Regional Partnerships

South Dakota State Univ., Brookings, SD
Cornell University, Ithaca, NY
Univ. of Tennessee, Knoxville, TN
Oklahoma State Univ., Stillwater, OK
Oregon State Univ., Corvallis, OR

Modified 10/1/2008

Biofuel Challenges: Energy Density

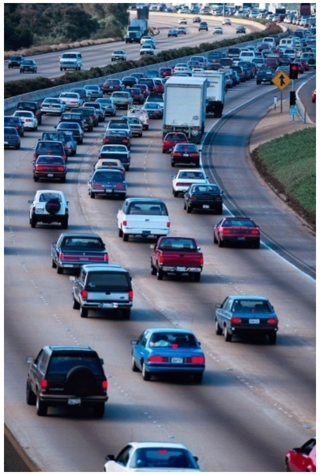
Cellulosic ethanol addresses the gasoline market

- U.S. gasoline usage: 140 billion gallons/year
- Doesn’t address need for higher-energy density fuels

Energy Densities (Lower Heating Value)

Ethanol	Gasoline	Biodiesel	Diesel/Jet Fuel
76,330 Btu/gal	116,090 Btu/gal	118,170 Btu/gal	128,545/135,000 Btu/gal

- U.S. petroleum diesel: 66 billion gallons/year
- U.S. jet fuel: 25 billion gallons/year



The Biodiesel Dilemma

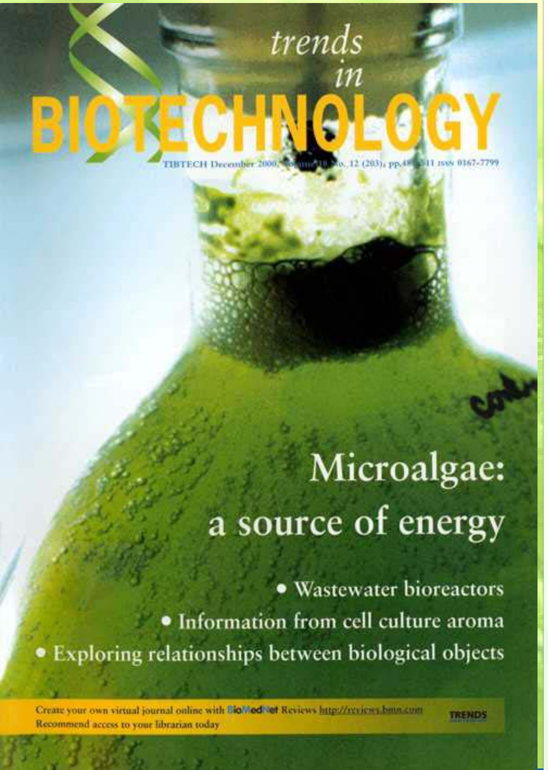
Triglycerides (TAGs) from oilseed crops/waste oils can't meet U.S. diesel demand (60+ billion gal/yr)

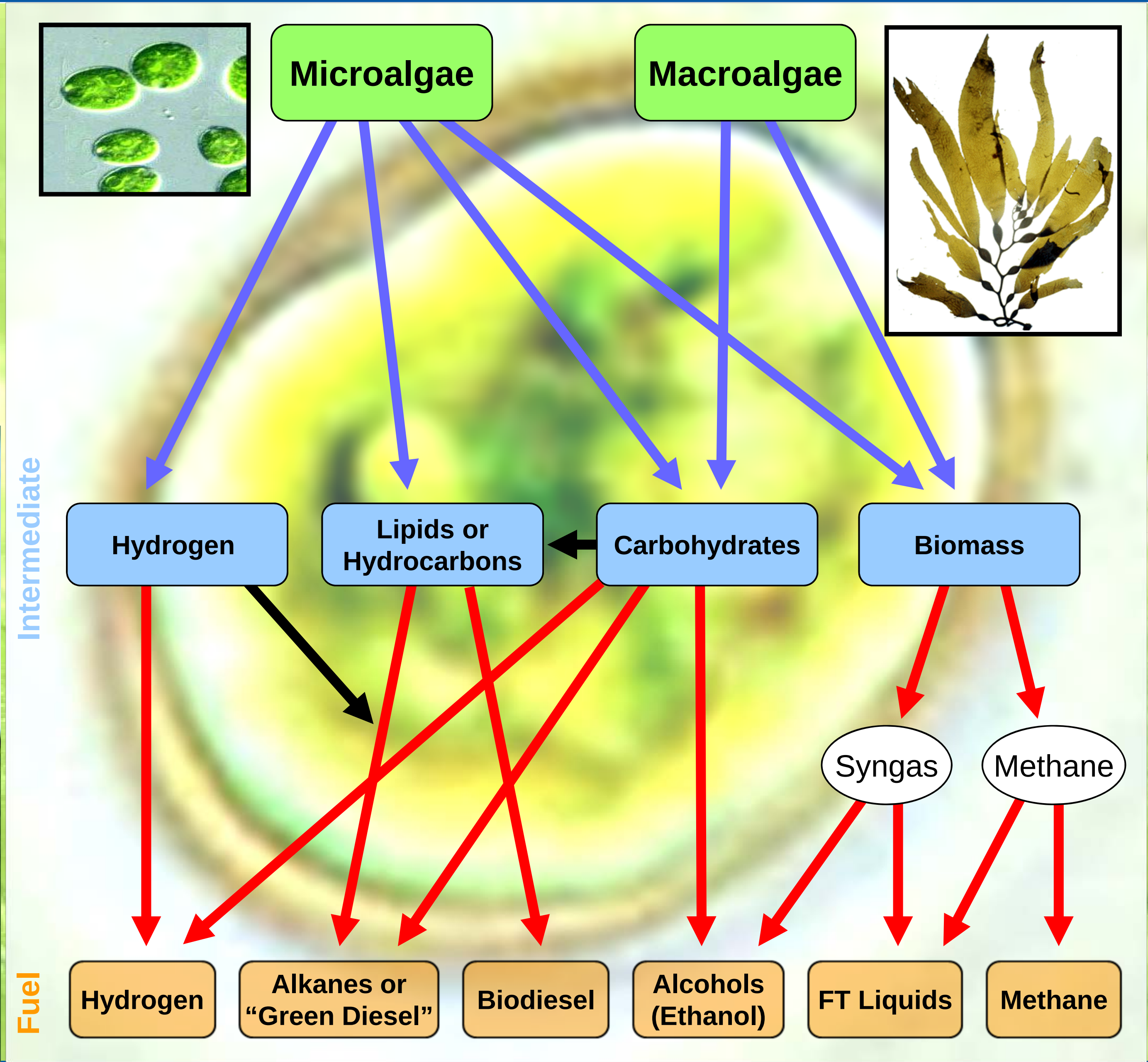
- ~ 3 billion gallons soy oil/year (US)
- Replaces ~5% of diesel fuel usage.
- Cannot use biodiesel to replace jet fuel
- Variable input costs – competes with high valued food market
- US has 2.5B gallon capacity, only 700M gallons produced in 2008

Alternative sources of TAGs are needed!

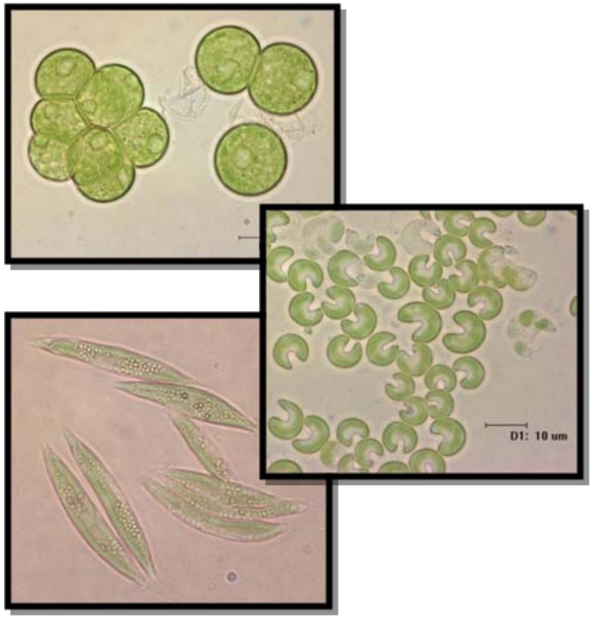
Algae: Numerous Bioenergy Routes

Defining a Biofuels Portfolio From Microalgae



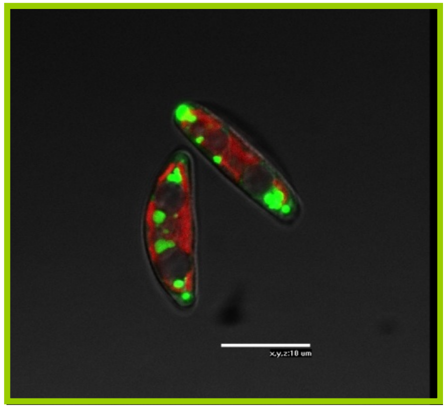


Why Fuels from Algal Oil?

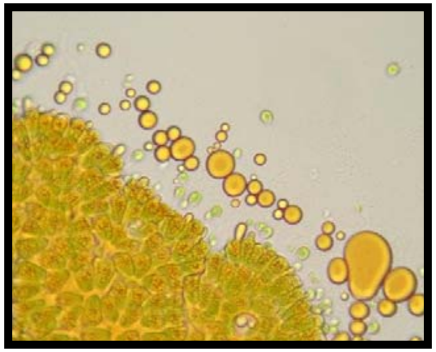


Images courtesy:
Lee Elliott, CSM

- **High-lipid content (up to 60%); rapid growth; highly productive (tons per acre); more lipids than terrestrial plants**
- **Can use non-arable land; saline/brackish water**
- **No competition with food, feed or fiber**
- **Utilize large waste CO_2 resources (i.e., flue gas)**
- **Potential to displace significant U.S. petroleum fuel usage**



Fluorescence micrograph showing stained algal oil droplets (green)



Superior Oil Yields

Crop	Oil Yield Gallons/acre
Corn	18
Cotton	35
Soybean	48
Mustard seed	61
Sunflower	102
Rapeseed	127
Jatropha	202
Oil palm	635
Algae (20g/m^2/day-15%)	1267

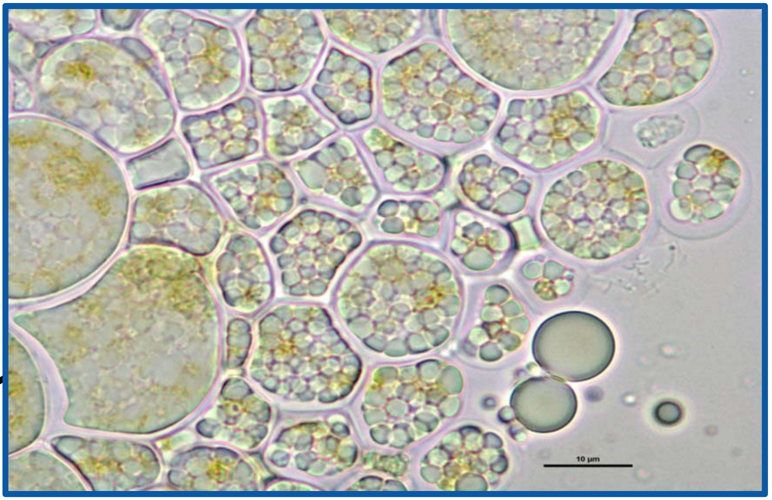
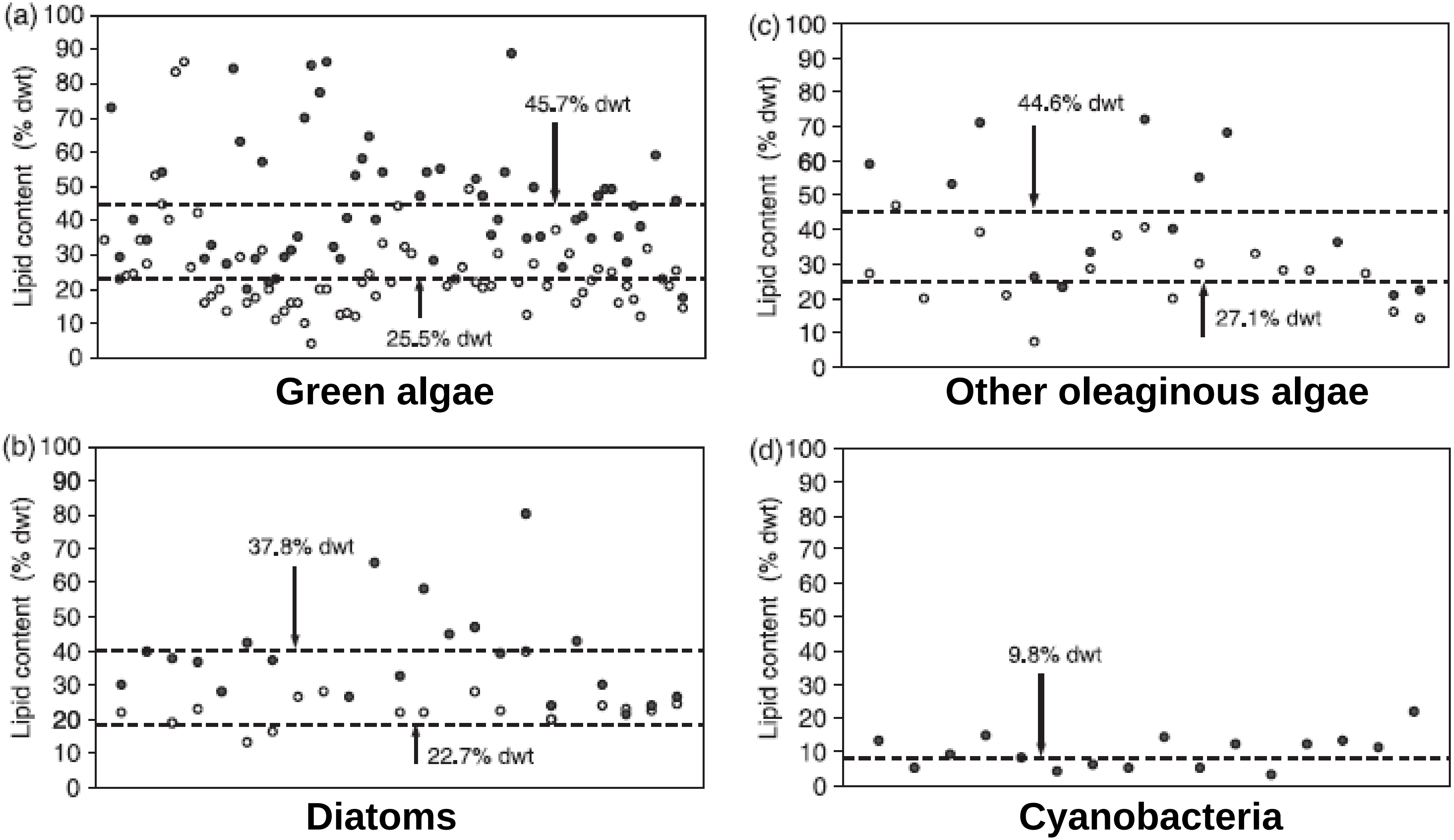


Image courtesy of Lee Elliott, CSM

Cellular Lipid Content of Algae

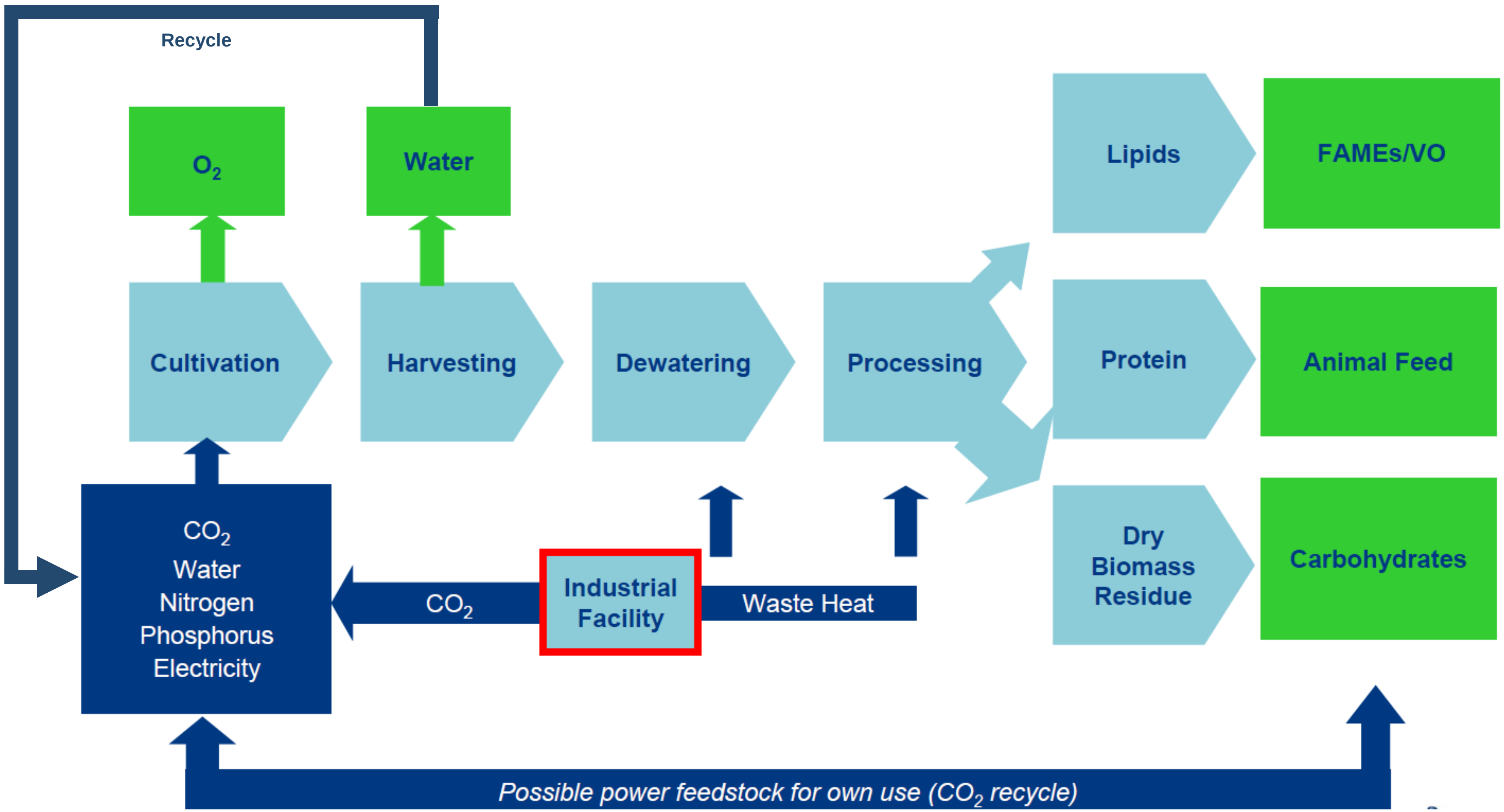


Hu, Q., Sommerfeld, M., Jarvis, E., Ghirardi, M., Posewitz, M., Seibert, M. and Darzins, A. (2008) Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. The Plant Journal 54:621-639.

Algae Compared to Ethanol Crops

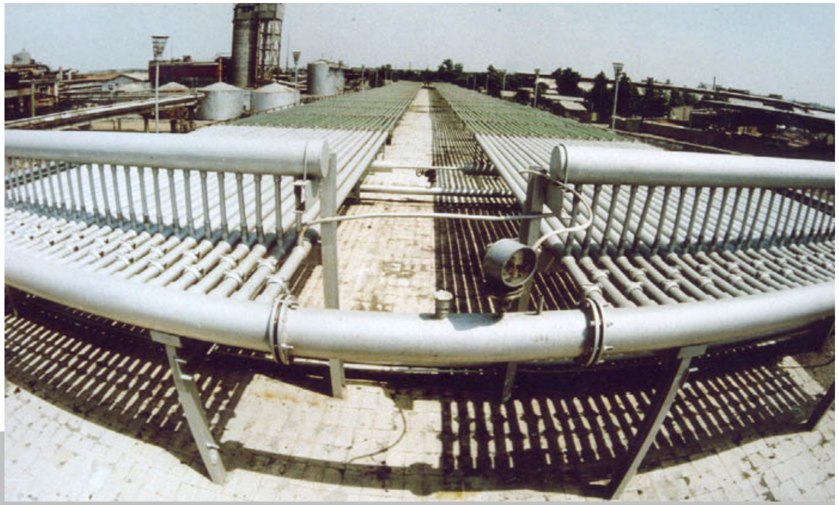
Biomass	Productivity	Energy (GJ/acre) 90 MJ/gallon ethanol 128 MJ/gallon oil
Sugar Cane	35 tons/acre 700 gal/acre - sugar 1440 gal/acre - bagasse	62 GJ/acre (sugar to ethanol only) 191 GJ/acre (sugar and bagasse)
Corn	8 tons/acre 405 gal/acre - grain 420 gal/acre – corn stover	36 GJ/acre (starch to ethanol only) 72 GJ/acre (grain and corn stover)
Algae	32 tons/acre (20 gm/m^2/day @15% oil) 1267 gallons/acre	162 GJ/acre (oil only)
	49 tons/acre (30 gm/m^2/day @15% oil) 1899 gallons/acre	243 GJ/acre (oil only)
	49 tons/acre (30 gm/m^2/day @ 30% oil) 3799 gallons/acre	486 GJ/acre (oil only)

General Cultivation and Processing



Photobioreactors

Open System



Closed System

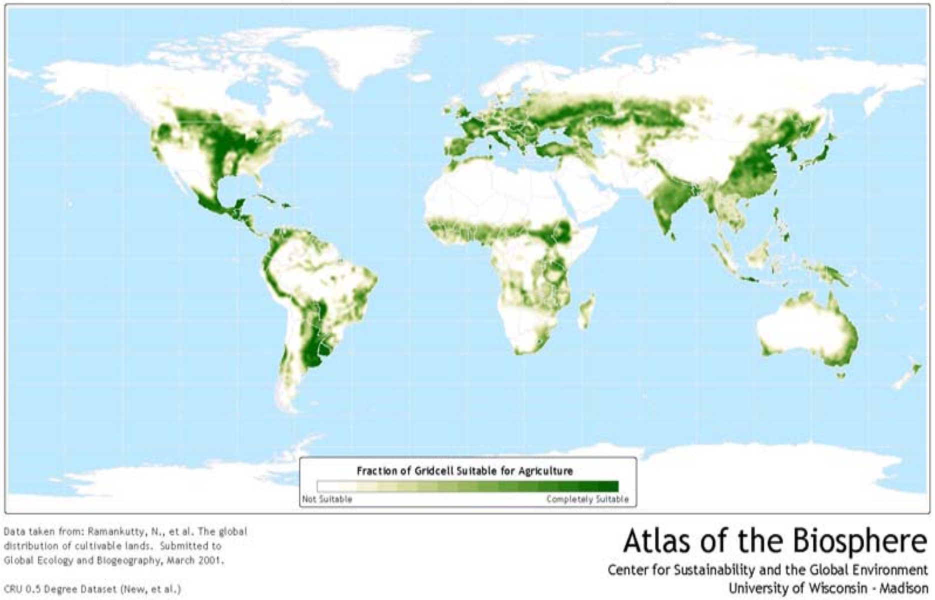
Cyanotech - Open Culture Ponds

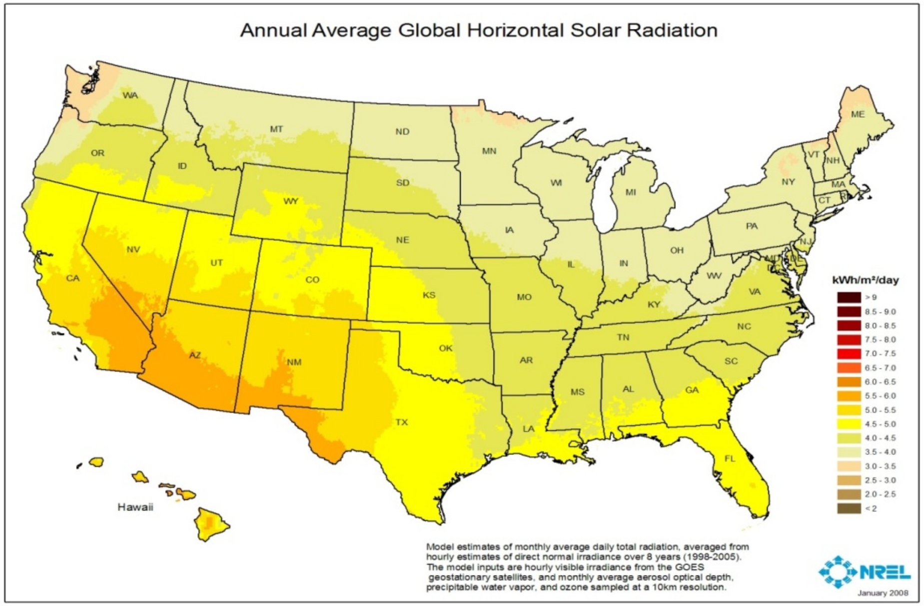
Kona, Hawaii

Photobioreactor examples

Land Resources

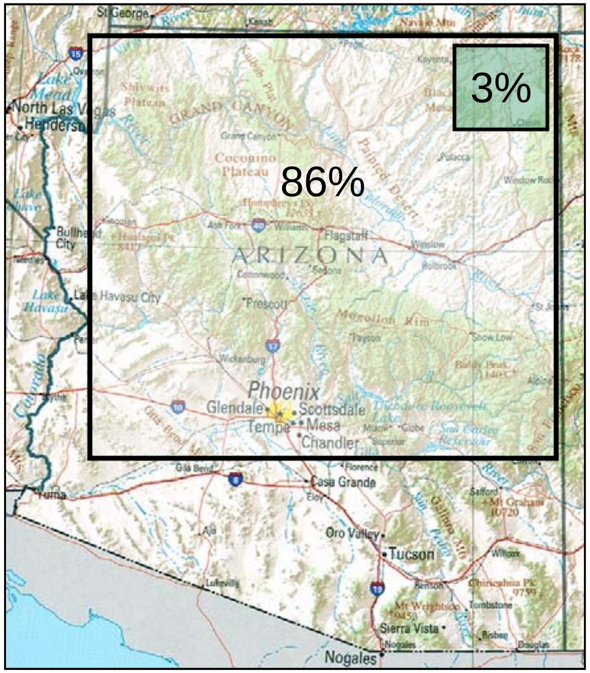
Vast Areas of the Globe Are Not Suitable for High Levels of Terrestrial Agriculture…..





…..but vast areas of the US could be an ideal location for algal cultivation.

Resource Requirements

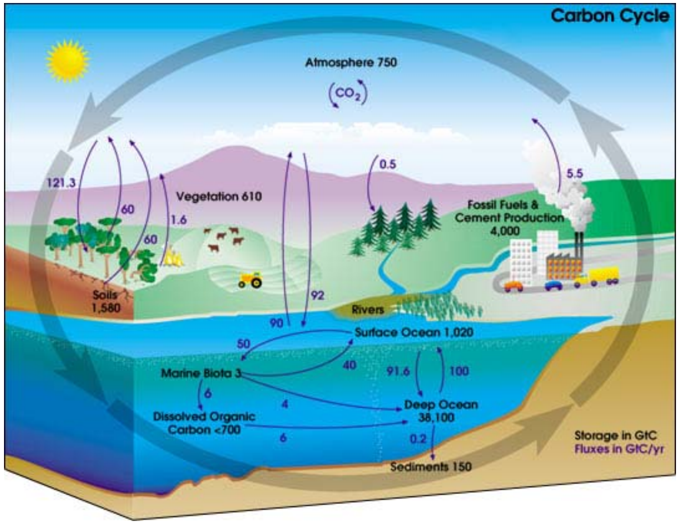


	Soybean	Algae*
gal/year	3 billion	3 billion
gal/acre	48	1267
Total acres	62.5 million**	2.4 million
Water usage	ND	6 trillion gal/yr***
CO_2 fixed	ND	79 million tons/yr

* algae (open ponds) productivity of 10 g/m^2/day with 30% TAG.

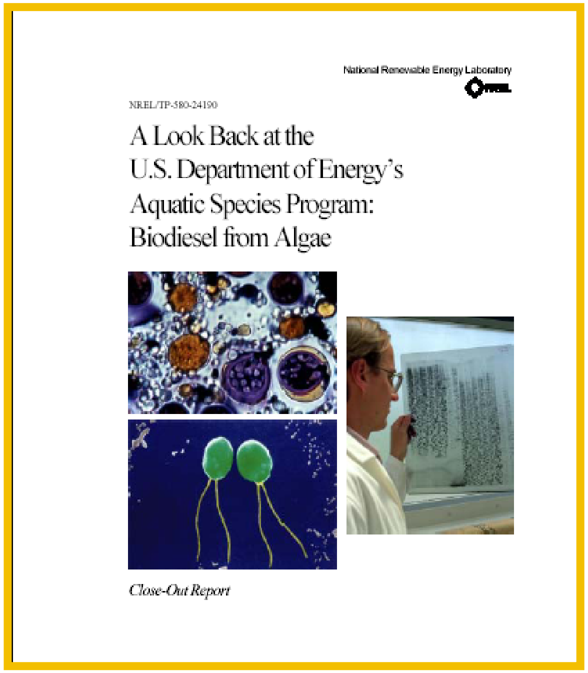
** Total land area: 73 million acres

*** 50 trillion gallons used annually for irrigation of crops in the US



- World emits ~ 32 Gt CO_2 ; ~17 Gt is absorbed;15 Gt remains in atmosphere
- 1 Gt CO_2 can produce ~40 B gallons algal oil
- Average coal power plant (600-700 MW) produces 4M tons CO_2 per year

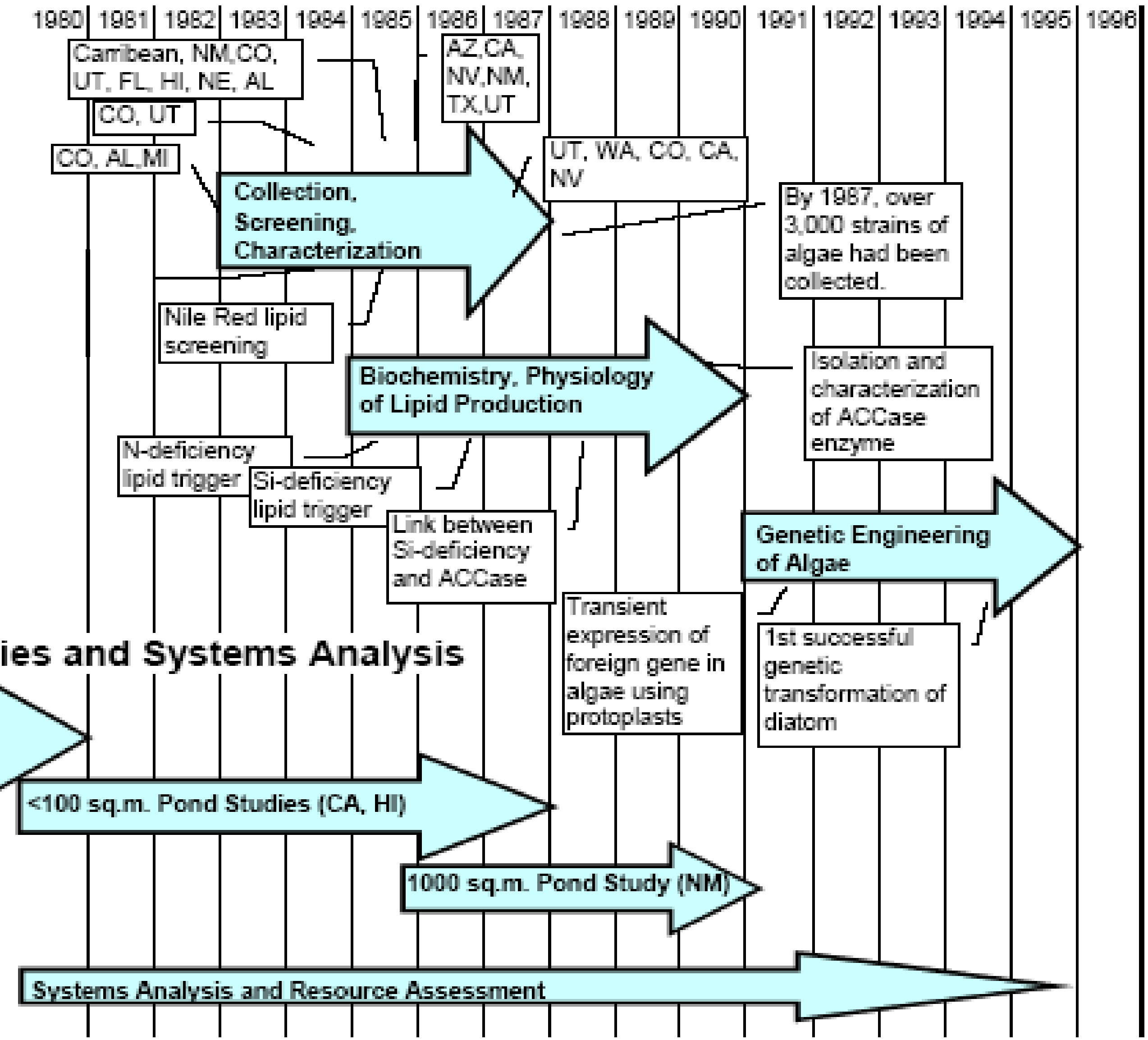
DOE's Aquatic Species Program

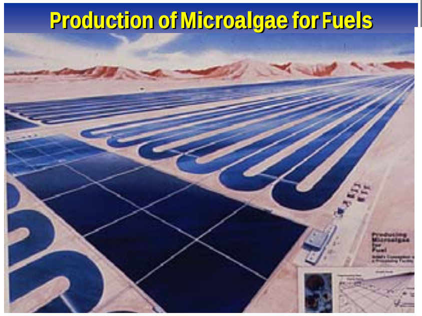

National Renewable Energy Laboratory

NREL/TP-580-24190

A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae

Close-Out Report





What's Changed Since 1996?

- **Record oil prices; increasing demand**
- **CO_2 capture and GHG reduction**
- **Industrial interest (>200 algal companies)**
- **Interest by academia, oil industry, end users, utilities and Federal government agencies**

Chevron

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
UNITED STATES AIR FORCE

ConocoPhillips

DARPA

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

NREL

Sandia National Laboratories

Pacific Northwest National Laboratory

NETL

Los Alamos NATIONAL LABORATORY EST. 1943

Venture Capital Investments Heating Up

Venture Capital firms invested $280M in advanced biofuels (Q1-Q2 2008); $84 M for algae biomass; by comparison, $4M invested for algae Q3 2007

LiveFuels: raised $10M Series A (2007)

Aurora BioFuels: raises $20M; open-pond, algae oil production

Sapphire Energy: raises $50M first round; additional $50M raised

Solazyme: raises $45M; heterotrophic growth

Algenol Biofuels: $850M investment from Mexico’s BioFields; ethanol from Cyanobacteria

Algal Biofuels in the News……

NBC Nightly News with Brian Williams

npr

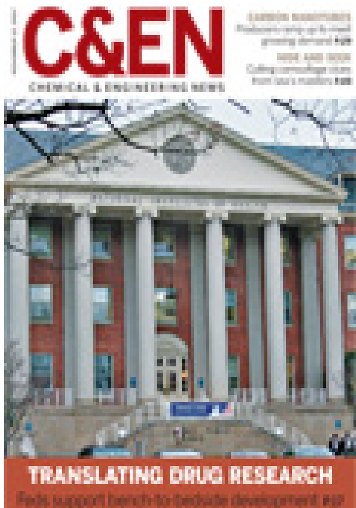
nature.com

San Jose Mercury News

American Public Media

Houston Chronicle

Esquire



American RadioWorks®

nature biotechnology

AP Associated Press

FT.com FINANCIAL TIMES

the Salina Journal

CNN

msnbc

PLENTY THE WORLD IN GREEN

THE WALL STREET JOURNAL.

Austin American-Statesman statesman.com

San Francisco Chronicle

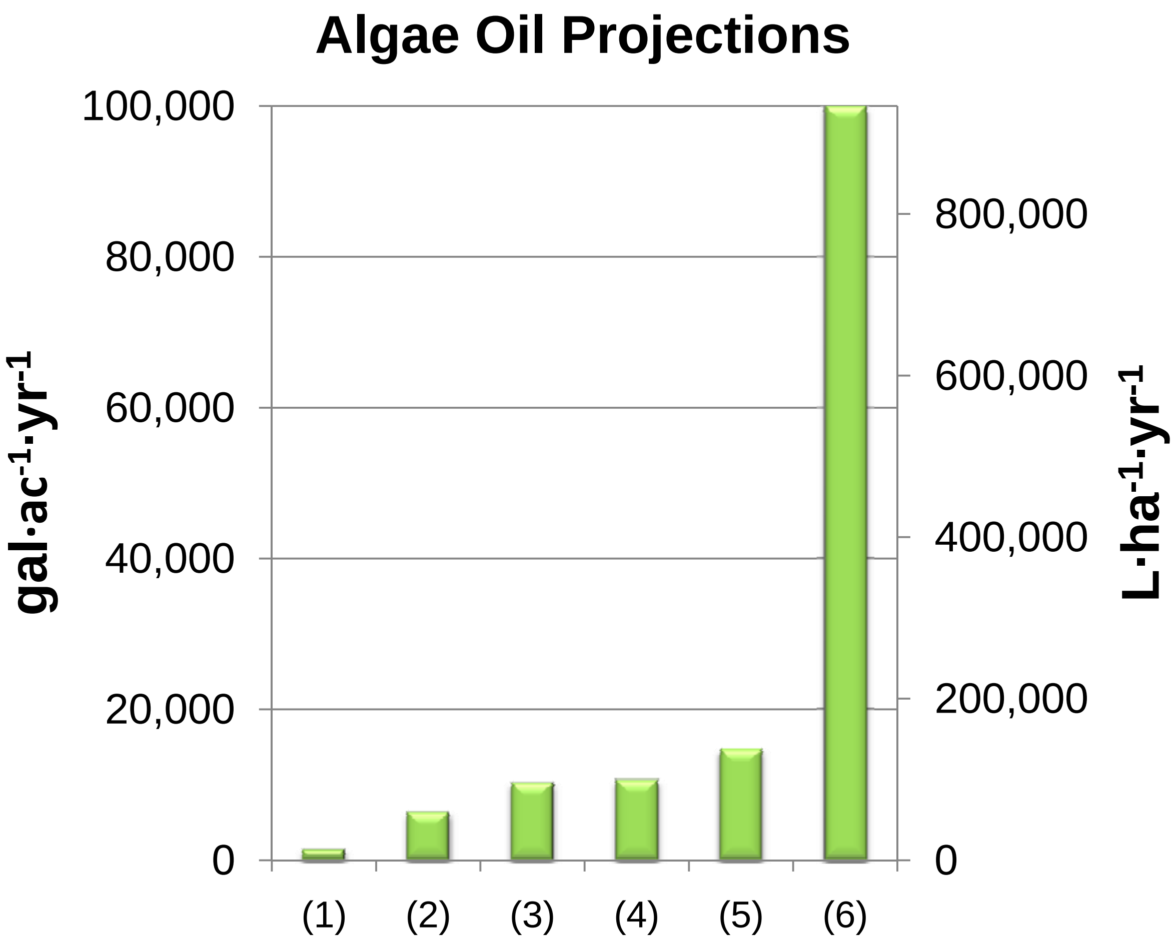
CNNMoney.com

Huge Potential for Algal Biofuels

- Scenarios for producing substantial amount of diesel from microalgae are not unrealistic
- A major 'dedicated" effort will be necessary to make this vision a reality
- Significant R&D involving both <u>biology</u> and <u>engineering</u> will be required to realize realistic scenarios

- US federal government is now showing significant interest

Myth vs Reality



(1) Schenk, 2008
(2) Chisti, 2007 **(30% oil)**
(3) NREL ASP, Sheehan et al., 1998
(4) Schenk, 2008
(5) Chisti, 2007 **(70% oil)**
(6) Report on CNN, Apr 4, 2008

Wide range of projections…

What is the ultimate upper limit?

K. Weyer-Geigel, D. Bush, A. Darzins and B. Willson. (2009). Theoretical Maximum Algal Oil Production. (Bioenergy, *submitted*)

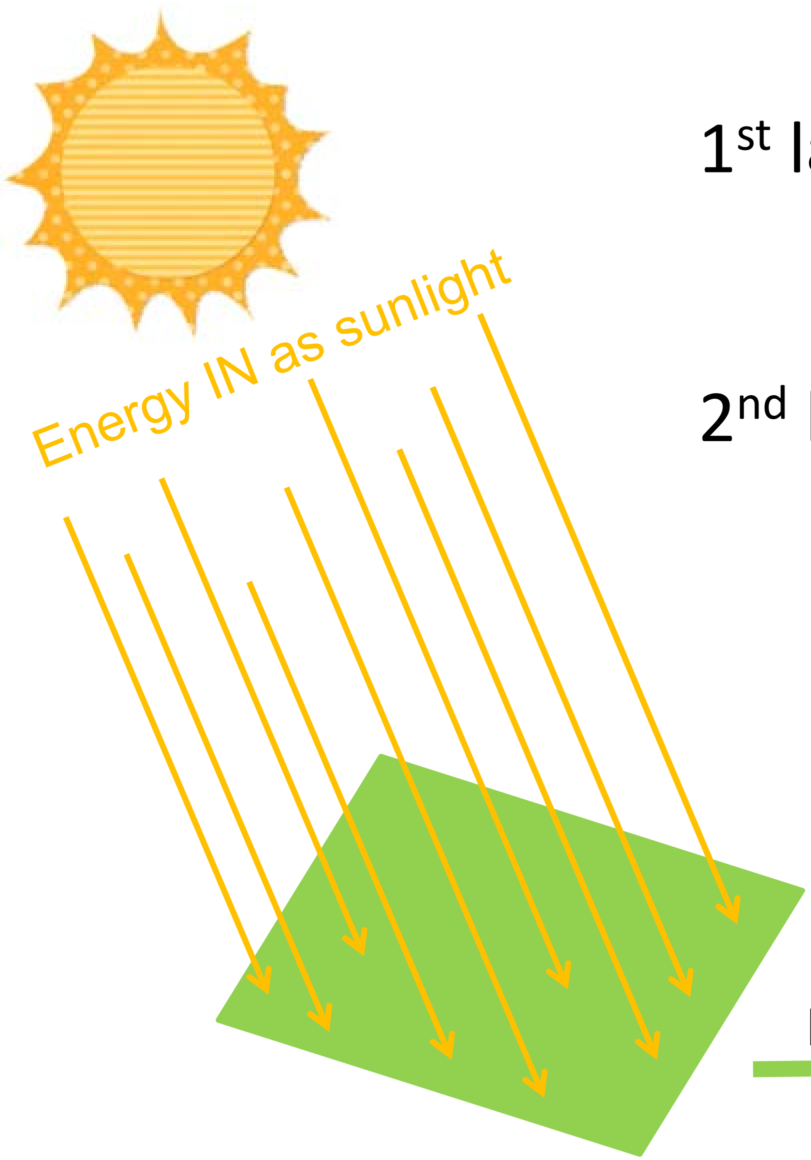
Need to Obey Laws of Thermodynamics

1st law: conservation of energy

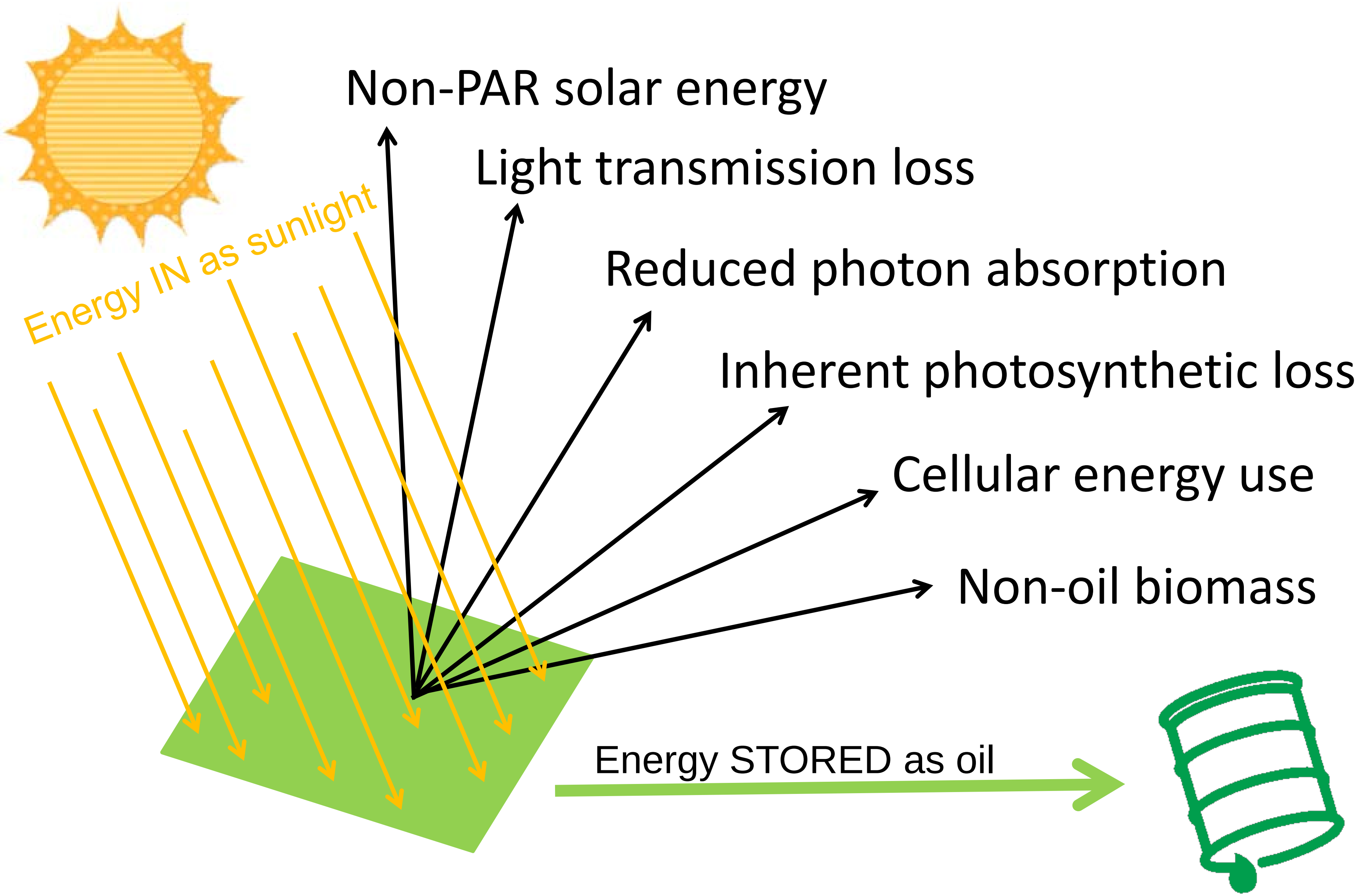
$$E_{in} - E_{out} = E_{stored}$$

2nd law: 100% efficiency is not possible

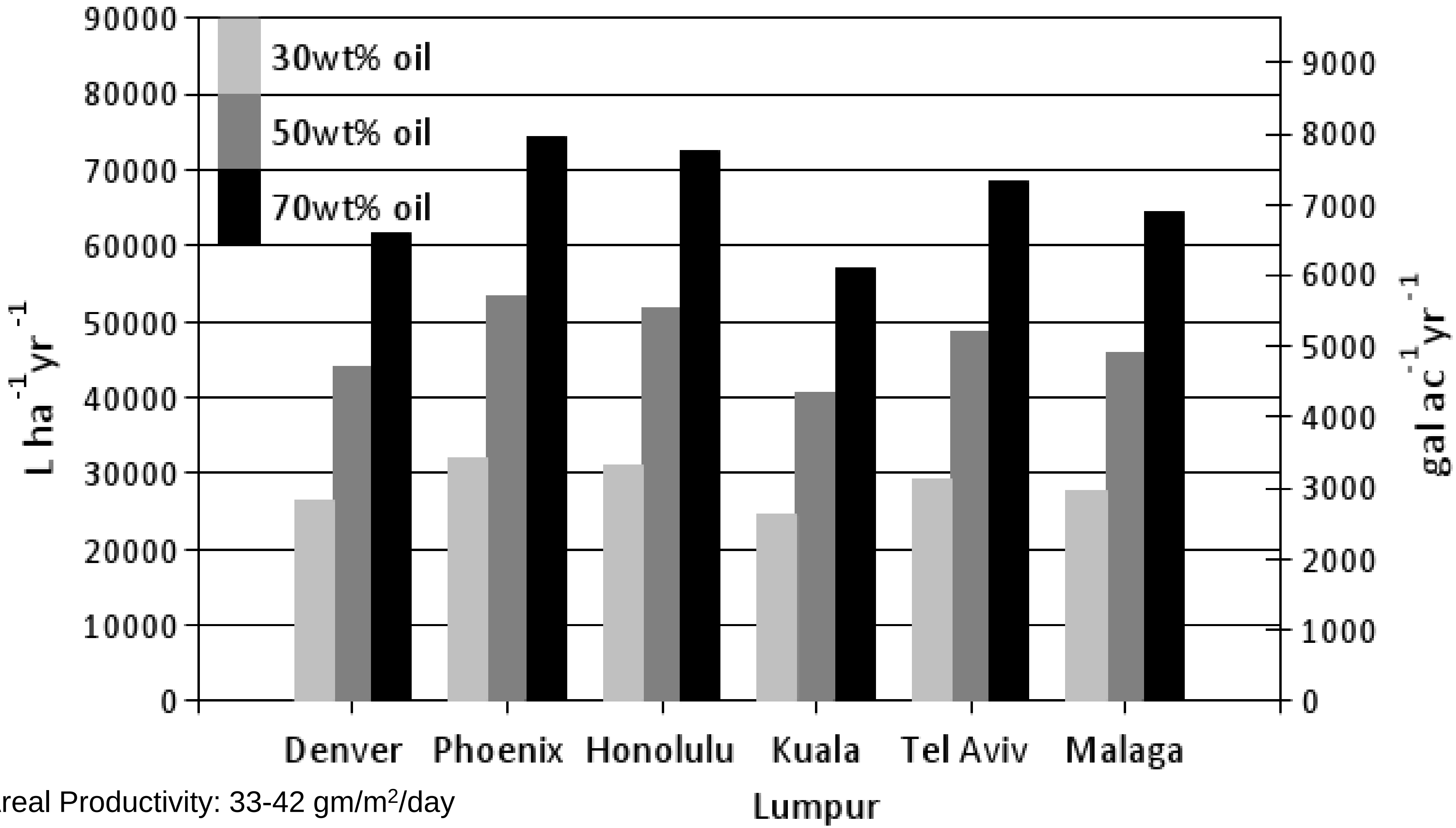
$$E_{in} > E_{stored}$$



Inefficiences galore.....



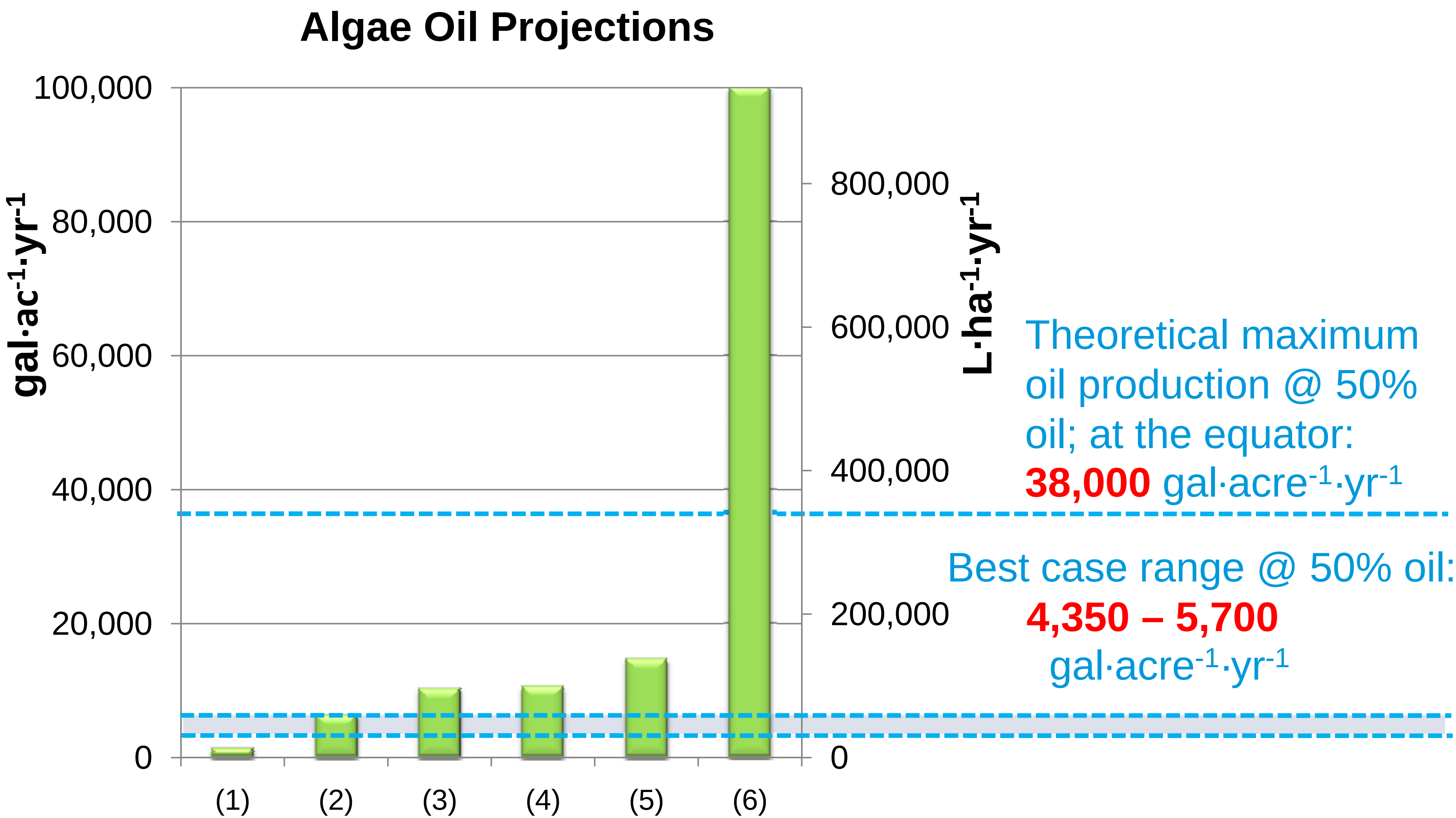
Algal Oil Production Projections



Areal Productivity: 33-42 gm/m^2/day

K. Weyer, D. Bush, A. Darzins and B. Willson. (2009). Theoretical Maximum Algal Oil Production. (BioEnergy Research)

Industry needs to well grounded….



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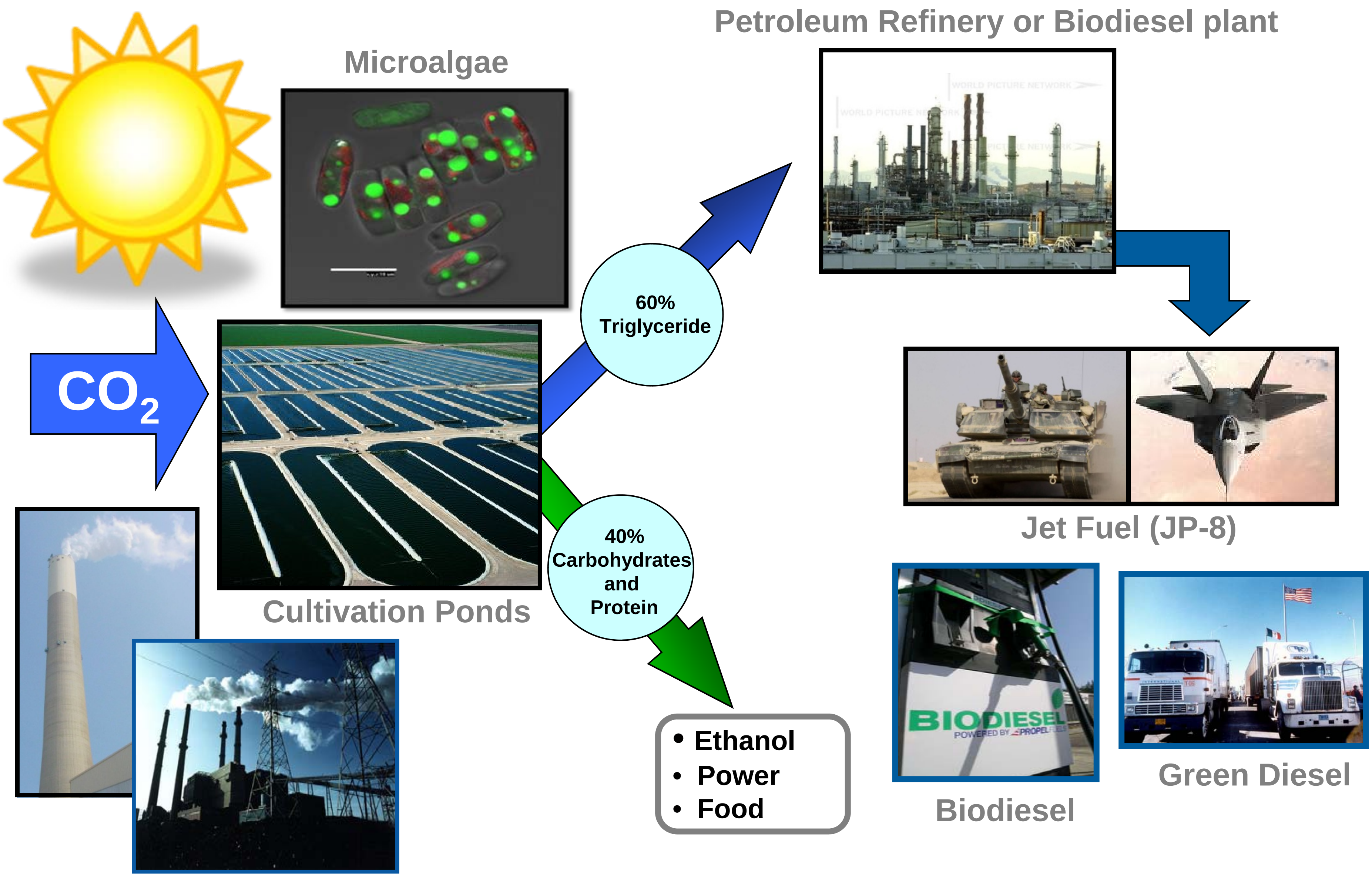
Fuels from algae….simple in theory



Significant challenges still exist

Algal Cultivation

Photobioreactor design
Capital and operating costs
Temperature control
Makeup water (evaporation)
CO_2 availability and transport
Nutrient requirements (N, P)
Starting species
Growth rate
Oil content & FA profile
Robustness
Resistance to invasion
Biofouling in closed systems
Nutrient induction requirement
Environmental impact, containment

Oil (Lipid) Recovery

Harvesting
De-watering methods
Lipid extraction
Purification
Costs, energy input
Environmental issues
Value from residual biomass

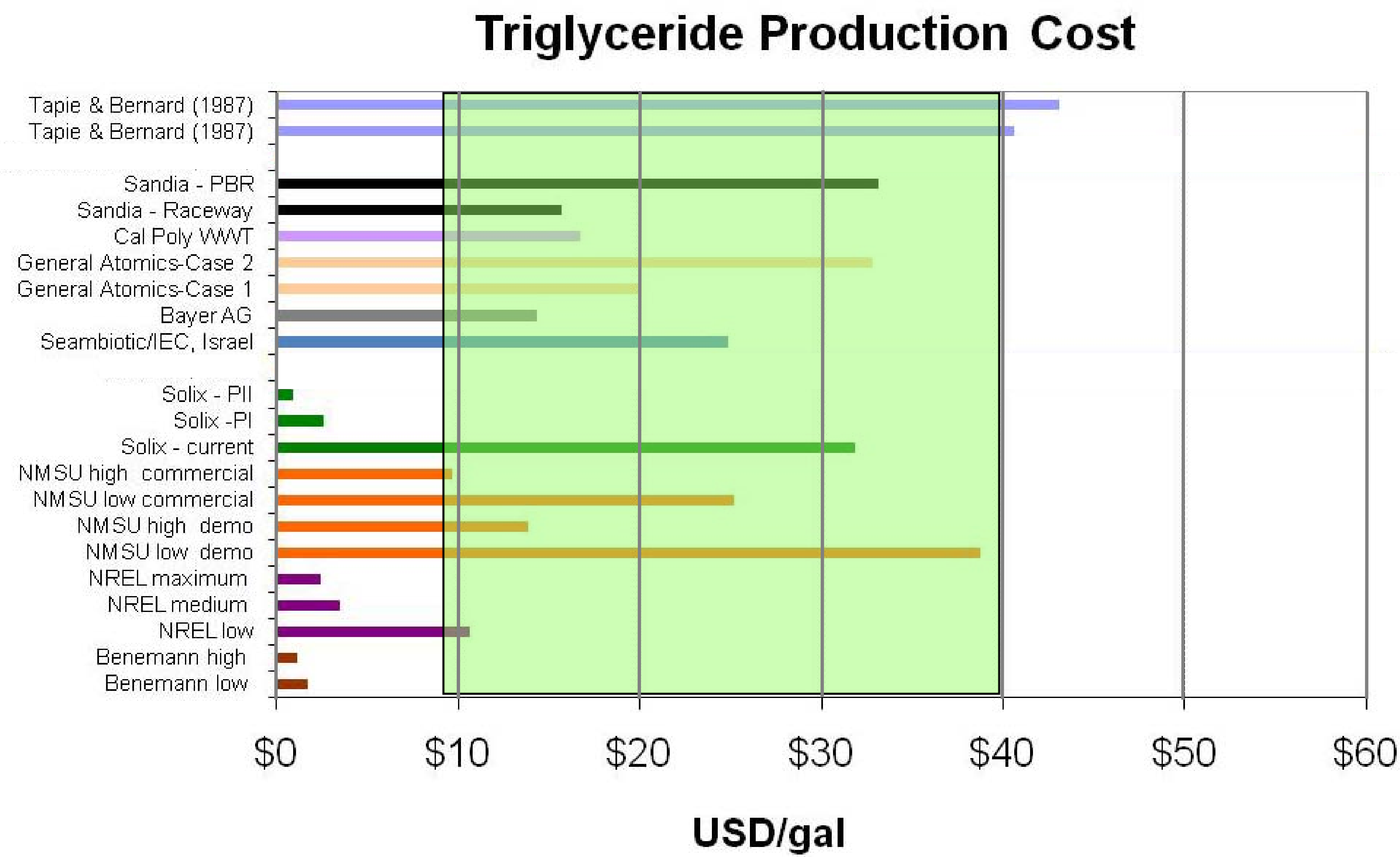
Fuel Production

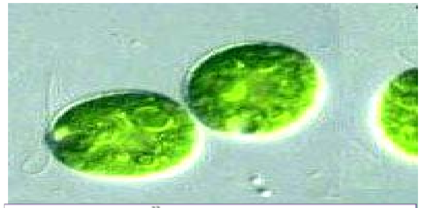
Process optimization
Fatty acid profiles
Costs and LCA
Fuel characteristics
- Energy density
- Carbon numbers
- Cloud point
- Stability
- Consistency

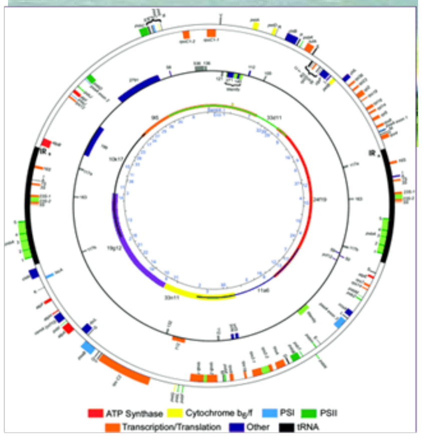
Additives required
Engine testing
ASTM standard

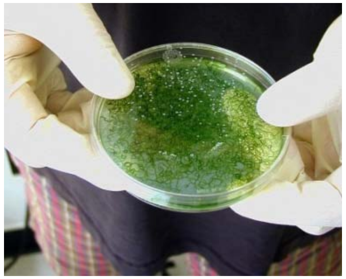
Sustainable Water, Land and Nutrient Use

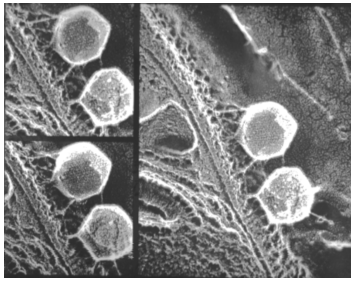
Standardized Cost Comparison

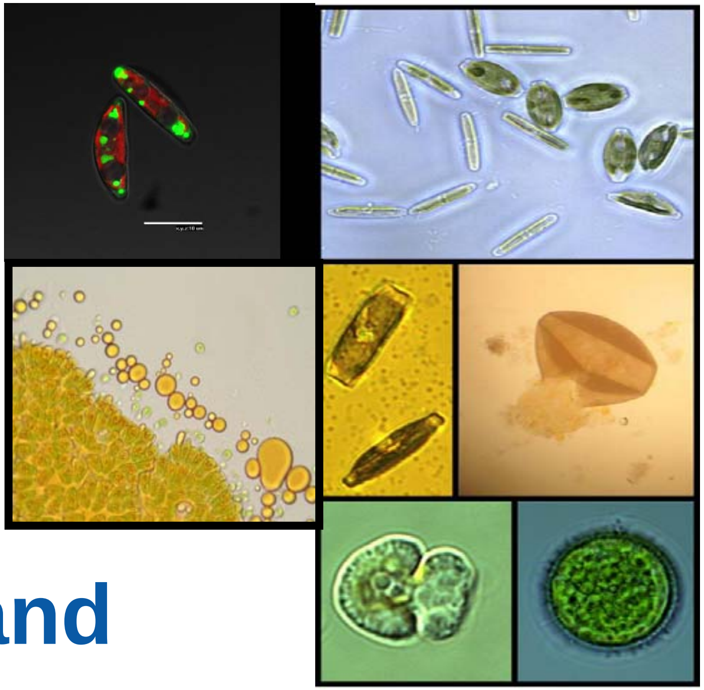




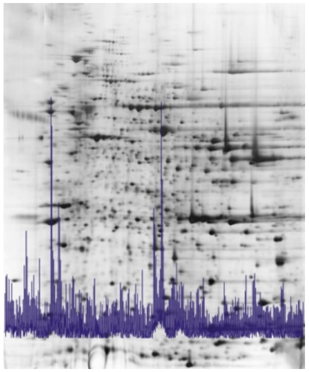


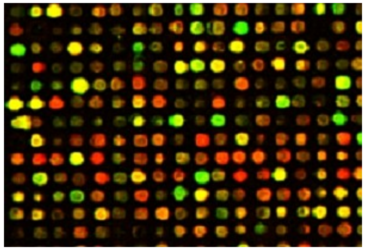


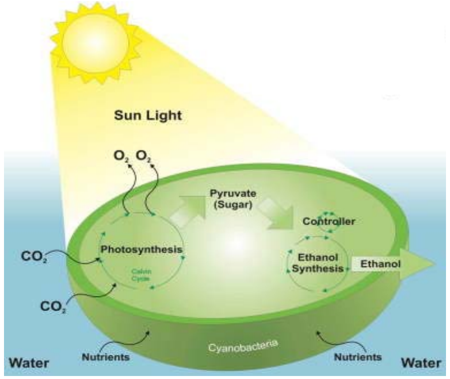


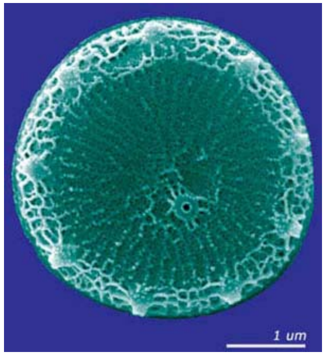


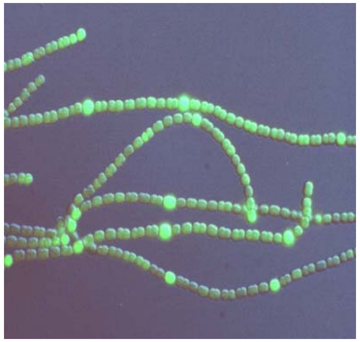
Recent Algal Biofuels Reports and Roadmapping Activities











Congressional Algae Report

2007 Energy Independence and Security Act (EISA)

- Increase availability of renewable energy that decreases GHG emissions
- Increases Renewable Fuel Standard (RFS) to 36 B gallons by 2022.
- (Section 228) Requires Energy Secretary to present to Congress a report on the feasibility of microalgae as a feedstock for biofuels production

Congressional Algae Report

Microalgae Feedstocks for Biofuels Production

Report to Congress

Microalgae Feedstocks for Biofuels Production
(EISA 2007 – Section 228)

March 14, 2008

U.S. Department of Energy

Report Outline

- Executive Summary
- Introduction
- Historical Review of Technical Progress
- Microalgae Oil Production: Biology and Physiology
- Microalgae Oil to Biofuels
- Current Activities/Funding Support for Algae Biofuels
- Resource and Technoeconomic Assessment
- Conclusions and Recommendations

National Renewable Energy Laboratory
and
Air Force Office of Scientific Research
Joint Workshop
on
Algal Oil for Jet Fuel Production

February 19-21, 2008

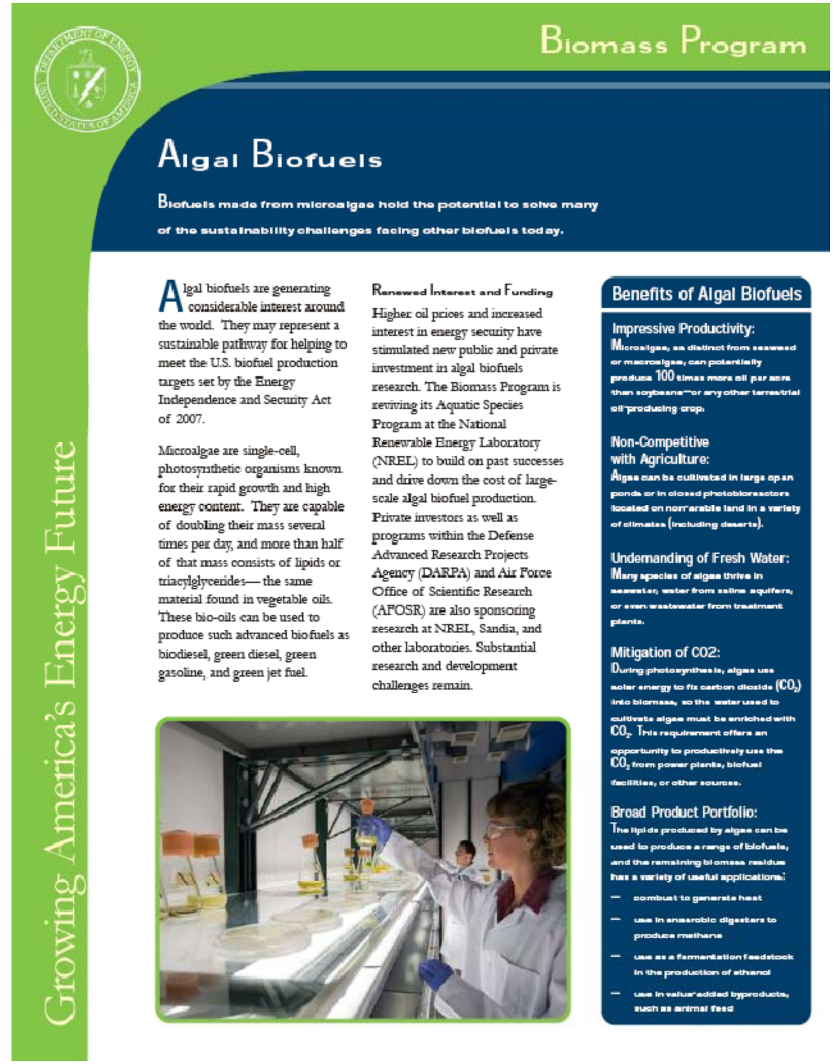
Arlington, VA

http://www.nrel.gov/biomass/algal_oil_workshop.html

Algal Biofuels Technology Roadmap Workshop

Sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Office of the Biomass Program

- **Venue**: Univ. of Maryland Dec 9-10, 2008
- **Participants**: ~200 scientists, engineers and other experts and stockholders
- **Goal**: Define activities needed to resolve barriers associated with commercial scale algal biofuel production
- **Workshop**: plenary talks and breakout sessions covering technical, industrial, resource, and regulatory aspects
- **Information**: http://www.orau.gov/algae2008/
  http://www.orau.gov/algae2008pro
- **Progress**: First draft of Roadmap complete; Scheduled to be released Fall 2009



Biomass Program

Growing America's Energy Future

Algal Biofuels

Biofuels made from microalgae hold the potential to solve many of the sustainability challenges facing other biofuels today.

Algal biofuels are generating considerable interest around the world. They may represent a sustainable pathway for helping to meet the U.S. biofuel production targets set by the Energy Independence and Security Act of 2007.

Microalgae are single-cell, photosynthetic organisms known for their rapid growth and high energy content. They are capable of doubling their mass several times per day, and more than half of that mass consists of lipids or triacylglycerides— the same material found in vegetable oils. These bio-oils can be used to produce such advanced biofuels as biodiesel, green diesel, green gasoline, and green jet fuel.

Renewed Interest and Funding

Higher oil prices and increased interest in energy security have stimulated new public and private investment in algal biofuels research. The Biomass Program is reviving its Aquatic Species Program at the National Renewable Energy Laboratory (NREL) to build on past successes and drive down the cost of large-scale algal biofuel production. Private investors as well as programs within the Defense Advanced Research Projects Agency (DARPA) and Air Force Office of Scientific Research (AFOSR) are also sponsoring research at NREL, Sandia, and other laboratories. Substantial research and development challenges remain.

Benefits of Algal Biofuels

Impressive Productivity: Microalgae, as distinct from seaweed or macroalgae, can potentially produce 100 times more oil per acre than soybeans—or any other terrestrial oil-producing crop.

Non-Competitive with Agriculture: Algae can be cultivated in large open ponds or in closed photobioreactors located on non-arable land in a variety of climates (including deserts).

Undemanding of Fresh Water: Many species of algae thrive in seawater, water from saline aquifers, or even wastewater from treatment plants.

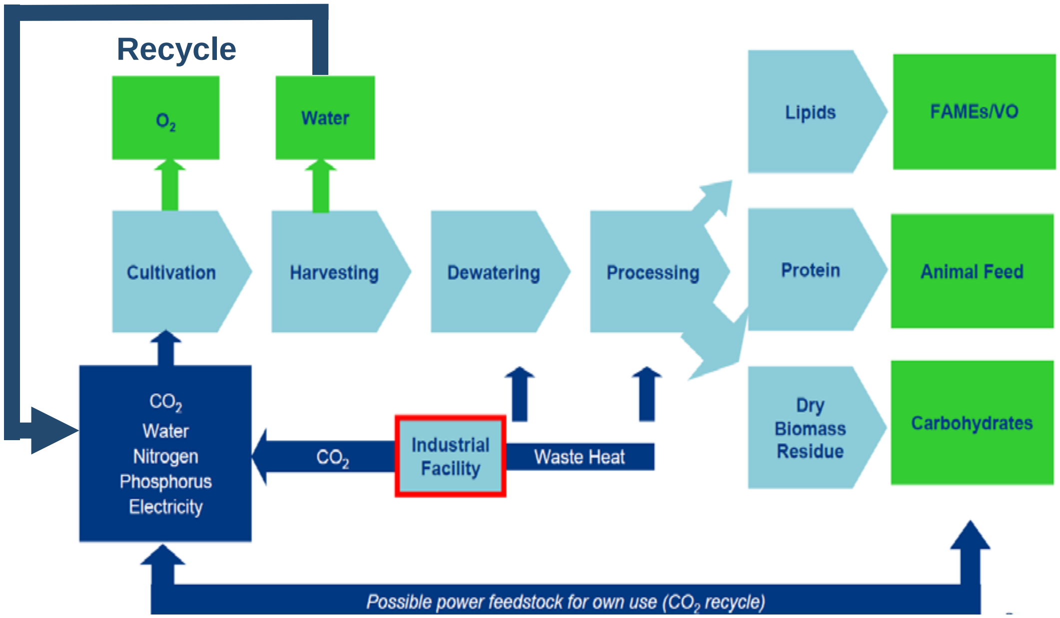
Mitigation of CO2: During photosynthesis, algae use solar energy to fix carbon dioxide (CO_2) into biomass, so the water used to cultivate algae must be enriched with CO_2. This requirement offers an opportunity to productively use the CO_2 from power plants, biofuel facilities, or other sources.

Broad Product Portfolio: The lipids produced by algae can be used to produce a range of biofuels, and the remaining biomass residue has a variety of useful applications:

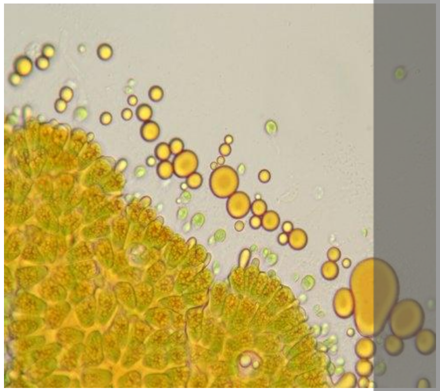
- combust to generate heat
- use in anaerobic digesters to produce methane
- use as a fermentation feedstock in the production of ethanol
- use in value-added byproducts, such as animal feed

http://www1.eere.energy.gov/biomass/pdfs/algalbiofuels.pdf

Fundamental and applied research needed to resolve uncertainties associated with commercial-scale algal biofuel production:



- Algal Biology
- Cultivation
- Harvest/dewatering
- Extraction/fractionation
- Conversion to fuels
- Co–products
- Systems integration
- Siting & Resources
- Regulation & Policy



Algal Biofuels Consortium Solicitation

A New EERE Center– a "Consortium"

Algal Biofuels Consortium

- Purpose is to "accelerate technology development"
- ARRA-funded competitive solicitation -- $50M for 3 yrs

Primary objective – "develop cost effective algae-based biofuels that are competitive with petroleum counterparts"

Other items from DOE Special Notice:

- Focus on barriers from DOE's National Algal Biofuels Roadmap
- Not seeking to construct new facilities but leverage existing capabilities and resources.
- Partnerships emphasized, because suite of technologies is required

DOE's Key Technology Barriers

1. **Feedstock supply:** Strain development and cultivation
2. **Feedstock logistics:** Harvesting and extraction
3. **Conversion/Production:** Accumulation of intermediate and synthesis of fuels and co-products
4. **Infrastructure:** Fuel testing and standardization
5. **Sustainable Practices:** Life Cycle and Technoeconomic analyses, siting, and resources management

Re-establishment of NREL's Algal Biofuels Program

Chevron Algae CRADA

2nd Collaborative Research and Development Agreement (CRADA) under Chevron/NREL Alliance

Goal: Identify and develop algae strains that can be economically harvested and processed into finished transportation fuels

NREL Support to USAF

Air Force Office of Scientific Research (AFOSR) Collaboration

2007-2008

- Algal biofuels research program
- NREL-AFOSR algae workshop
  Feb 19-21, 2008 (Arlington, VA)

http://www.nrel.gov/biomass/algal_oil_workshop.html

2009-2011

- Continuing NREL-AFOSR collaboration: Biohydrogen/Bio-jet fuels
- NREL has been integrated into AFOSR Bio-jet research program

NREL Funded Algal Biofuels Projects

Laboratory Directed Research & Development (LDRD) Awards

"Development of a Comprehensive High-Throughput Technique for Assessing Lipid Production in Algae"

"Use of Digital Gene Expression (DGE): Tag Profiling for High Throughput Transcriptomics in Microbial Strains Involved in Advanced Biofuel Production"

"Biodiesel from *Cyanobacteria*"

"Regulated Enzymatic Disruption of Algal Cell Walls as an Oil Extraction Technology"

"Identification of Novel Promoters in Green Algal Species"

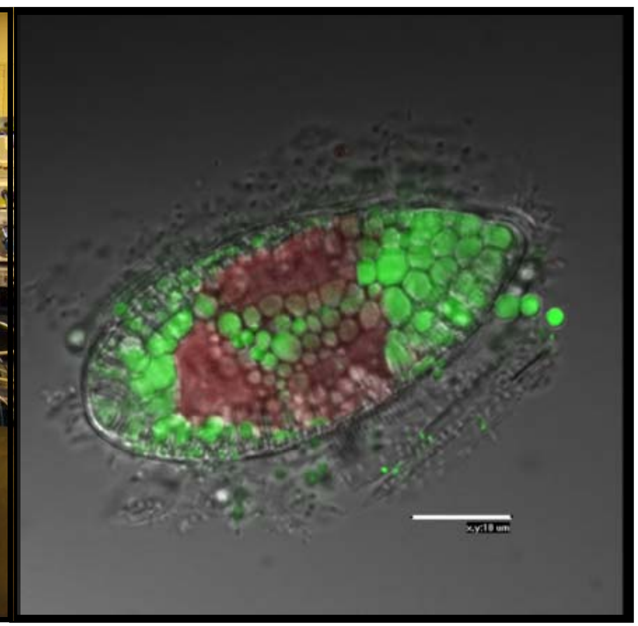
"Development of Novel Cyanobacterial Biofuels"

C2B2 Seed Grant Project

Colorado Center for Biorefining and Biofuels (C2B2) Seed Grant Award

“Establishment of a Bioenergy-Focused Microalgae Strain Collection Using Rapid, High-Throughput Methodologies”

National Renewable Energy Laboratory (NREL) and Colorado School of Mines



http://www.c2b2web.org

C2B2 Profit From Our Synergy Colorado Center for Biorefining and Biofuels

University of Colorado
Colorado State University
Colorado School of Mines
National Renewable Energy Laboratory

DOE US - Israel Collaboration

Development of Novel Microalgal Production and Downstream Processing Technologies for Alternative Biofuels Applications

Joint NREL/SNL/Israel-US Private Industry Collaboration

Tasks:

- Develop extraction methods
- Thermochemical conversion of algal feedstocks
- Physics-based modeling/analysis
- TE and Life Cycle Analysis (LCA)

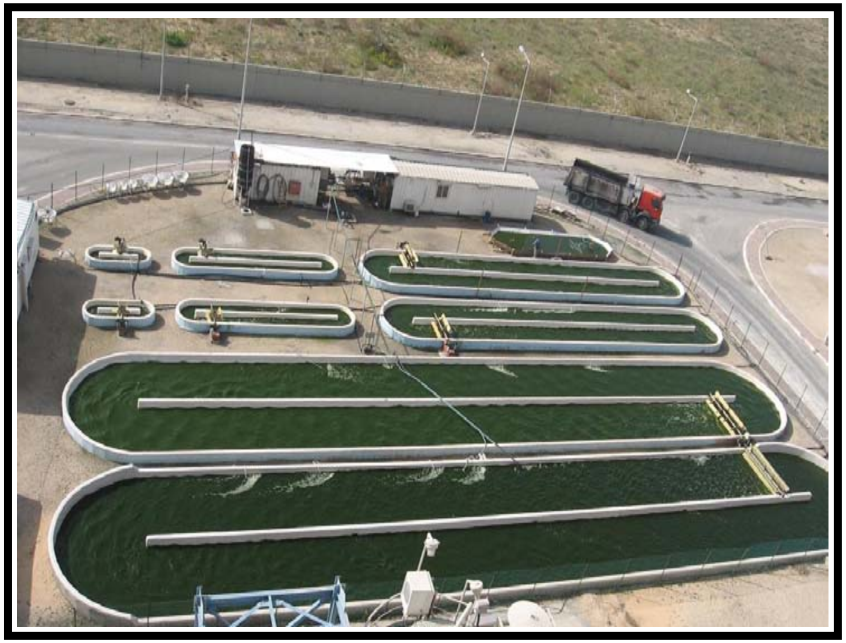
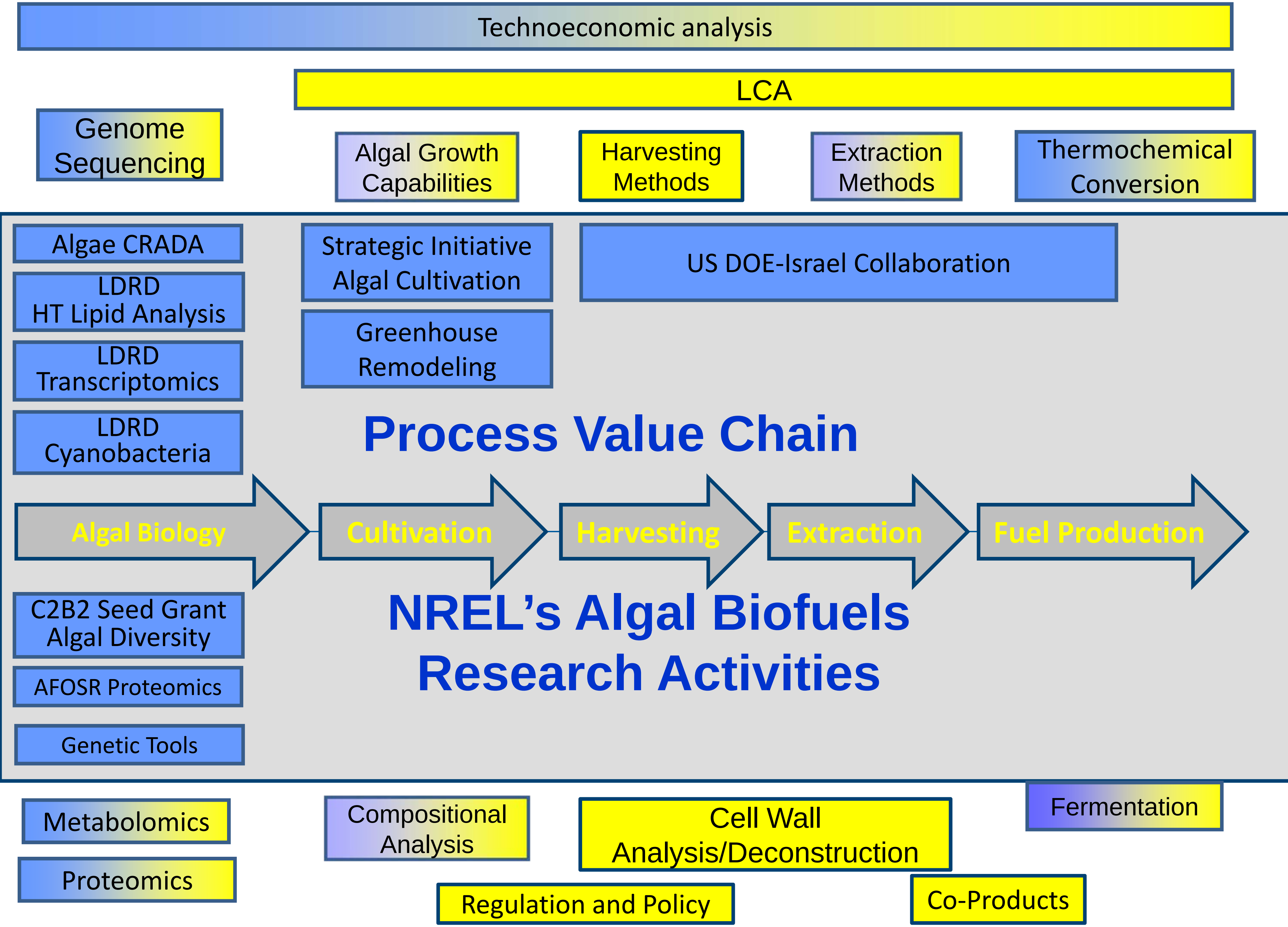


Image courtesy: A. Ben-Amotz, Seambiotic

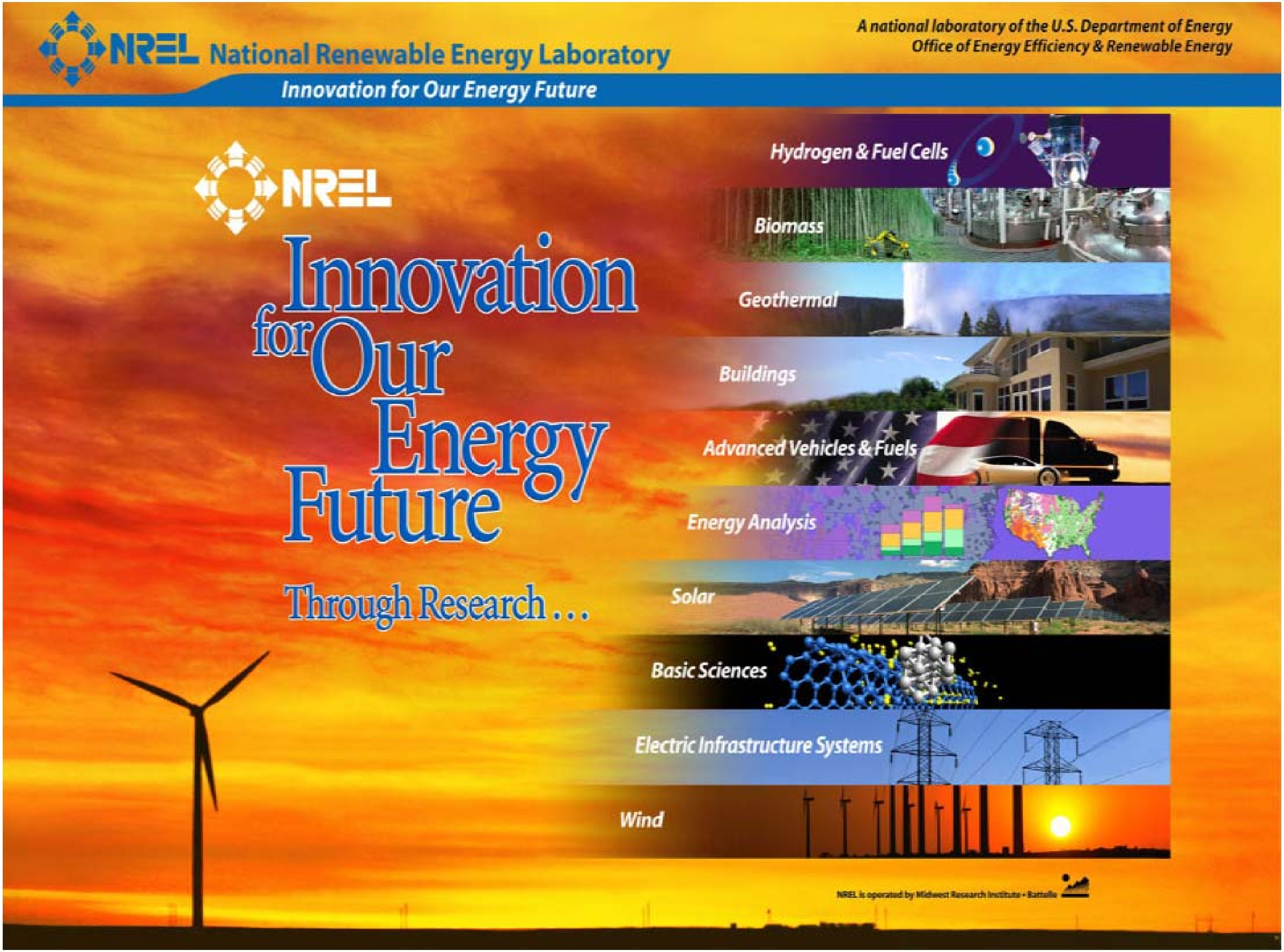
CEHMM.org Center of Excellence for Hazardous Materials Management

Seambiotic


Technoeconomic analysis
LCA
Genome Sequencing
Algal Growth Capabilities
Harvesting Methods
Extraction Methods
Thermochemical Conversion
Algae CRADA
LDRD HT Lipid Analysis
LDRD Transcriptomics
LDRD Cyanobacteria
Strategic Initiative Algal Cultivation
Greenhouse Remodeling
US DOE-Israel Collaboration
Process Value Chain
Algal Biology
Cultivation
Harvesting
Extraction
Fuel Production
C2B2 Seed Grant Algal Diversity
AFOSR Proteomics
Genetic Tools
NREL's Algal Biofuels Research Activities
Metabolomics
Proteomics
Compositional Analysis
Cell Wall Analysis/Deconstruction
Regulation and Policy
Fermentation
Co-Products

Conclusions

- Production of fuels from algae have been demonstrated.
- Algae can be grown, harvested; lipids extracted and converted to transportation fuels
- Algal biofuels are possible; can it be made economically and sustainably at a scale to help contribute to U.S. fuel demand?
- The potential of algal biofuels is significant
- A greater understanding of the underlying principles is necessary before commercial scale-up is feasible.
- Biological & engineering considerations are critical; fundamental/applied R&D will be needed.
- Needs coordinated support from relevant government agencies, private sector, academia, and stakeholders.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